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# SALT-STRESS-CORROSION CRACKING OF RESIDUALLY STRESSED Ti-8Al-1Mo-1V BRAKE-FORMED SHEET AT 550° F (561° K)

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# SALT-STRESS-CORROSION CRACKING OF RESIDUALLY STRESSED Ti-8Al-1Mo-1V BRAKE-FORMED SHEET AT 550° F (561° K)

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## SUMMARY

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An experimental investigation of salt-stress-corrosion cracking with residual stresses has been conducted with one of the supersonic-transport candidate materials, Ti-8Al-1Mo-1V. Specimens with right-angle bends were brake formed from sheet material to produce residual stresses, coated with sodium chloride, and exposed at 550° F (561° K). After various exposure times, some of the specimens were given a reverse-bend test to determine the extent of cracking based on bending deflection. Other specimens were examined metallurgically. Salt-stress-corrosion cracks began to appear in less than 20 hours, and the effects were at least as severe as the effects produced by load-induced tensile stresses. Several approaches were examined for alleviating the corrosion cracking, and, of these, shot peening and nickel plating appear promising enough to warrant further investigation.

Author

## INTRODUCTION

Materials evaluation screening tests for the supersonic-transport program have indicated that titanium alloys are prime candidates for structural application. Of the several titanium alloys available, Ti-8Al-1Mo-1V appears to be the most desirable for sheet application. However, many titanium alloys, including Ti-8Al-1Mo-1V, that exhibit good structural properties show poor resistance to salt-stress corrosion at elevated temperatures. Reference 1 has shown that severe salt-stress-corrosion cracking occurs at load-induced tensile stresses of 50 ksi (345 $MN/m^2$) when the material is exposed at a temperature of 550° F (561° K) for times as short as 500 hours.

Although titanium supersonic-transport design stress levels are considerably lower than 50 ksi (345 $MN/m^2$), load-induced stresses combined with residual stresses produced during fabrication can exceed 50 ksi (345 $MN/m^2$). These residual stresses are self-equilibrating; however, they can achieve high local values with tension as well as with compression on exposed surfaces, and they are present for the life of the aircraft unless relieved in some manner.

It is the purpose of this investigation to examine the influence of residual stresses on the salt-stress-corrosion cracking of brake-formed Ti-8Al-1Mo-1V sheet. A program has been conducted with two salt coatings and various exposures in air at 550° F (561° K) by using a unique specimen designed to simulate aircraft structural components with residual stresses. After exposure, a reverse-bend test and metallurgical examination are used to determine the effects of salt-stress-corrosion cracking. Several methods of corrosion-cracking alleviation including stress relief, shot peening, and nickel plating are explored.

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 2.

## EXPERIMENTAL PROCEDURES

### Specimens

The specimen design is shown in figure 1. This configuration was selected so that a small simple specimen could represent typical right-angle bends produced in the fabrication of structural stringers or frames. All specimens were brake formed on a 0.125-inch (3.2-mm) radius die at approximately 200° F (366° K) from 0.050-inch (1.27-mm) thick sheet. Bends were formed in the transverse grain direction to simulate actual structural stringer conditions. Specimen blanks were sheared from flat sheet and hand filed to remove shearing burrs prior to brake forming. After fabrication, the specimens were chemically cleaned.

The material used in this investigation was duplex-annealed Ti-8Al-1Mo-1V. Duplex annealing consists of 8 hours at 1450° F (1061° K) with a furnace cool followed by 15 minutes at 1450° F (1061° K) with air cooling. The tensile stress-strain curve presented in figure 2 is the representative one of four obtained from coupon tests of the sheet material from which the residually stressed specimens were made.

Sheet-metal bending has been studied by a number of investigators. (See, for example, ref. 3.) The calculation of residual stresses produced by a sheet-metal bending process is a complex problem; however, a simplified approach to the problem, Wöhler's method, is described in reference 4. When the stress-strain curve in figure 2 is used with Wöhler's method, a residual tensile stress of approximately 70 ksi (483 MN/m$^2$) is calculated for the inside surface of the 0.125-inch (3.2-mm) bend radius.

### Salt Application and Temperature Exposure

Pure sodium chloride was applied to the test specimens to form either a thick coating or a thin coating. (See fig. 3.) The thick coating was obtained by alternately dipping into a boiling supersaturated salt solution and drying over a hotplate. This process produced a uniform salt coating about 0.004 inch (0.1 mm) thick weighing $4.4 \times 10^{-4}$ lb (200 mg). Specimens coated in this manner will be referred to as "salt-coated" specimens.

Thin salt coatings were formed by dipping residual stressed specimens in a 3.4-percent solution of salt in water at room temperature. This salt percentage was chosen to represent a typical sea water concentration. After dipping, the specimen was dried in a position similar to that shown in figure 3. These salt-stress specimens retained only a thin coating of salt in the form of a transparent film with scattered salt crystals; weight of the dipped salt was $4.4 \times 10^{-6}$ lb (2 mg). A somewhat greater concentration of salt crystals occurred in the bend region due to surface tension of the solution while drying. Specimens treated in this manner will be referred to as "salt-dipped" specimens.

Bare, salt-dipped, and salt-coated specimens were subjected to continuous heating at 550° F (561° K) in noncirculating air ovens for various lengths of time up to 1800 hours. Specimens were removed from the ovens periodically and mechanically tested or metallurgically examined. For comparison purposes, one group of salt-dipped specimens were thermally cycled between room temperature and 550° F (561° K). Cycle time was defined as the exposure from specimen insertion into a preheated oven to specimen removal from the oven. Cycle times varied from 2 to 16 hours.

## Mechanical Tests

Existence of salt-stress-corrosion cracking in the residually stressed specimens after exposure to 550° F (561° K) was determined mechanically in a reverse-bend test at room temperature. (See fig. 4.) Load was applied at a constant testing-machine-ram-motion rate of 0.04 in./min (0.017 mm/s) until failure occurred. Autographic load-deflection curves, such as those plotted in figure 5(a), were recorded for many of the tests. The specimen loaded smoothly up to maximum load at which point a crack suddenly traversed through the thickness of the specimen at the midspan and failure occurred without additional deflection.

The reverse-bend test was selected because of the ease of testing and because it is the type of test that will provide a sensitive measure of the presence of cracks. If cracks develop due to salt, stress, and elevated temperature, they will initiate on the inside surfaces of the bend where the residual stress is tension. Reverse bending produces an increasing tension on the inside of the center-bend which is magnified by any cracks present. This tension results in early failure with only a little bending deflection. The bare specimen can be reverse bent until nearly flat. (See fig. 4(b).)

## Metallurgical Examination

Some specimens were examined metallurgically to determine the extent and depth of salt-stress-corrosion cracking. Most of these specimens had been mechanically tested first; however, a few specimens were examined without prior loading. The only significant difference observed in crack frequency or size was the failure crack which extended through the thickness of the specimens that had been mechanically tested. The specimens were edge mounted in plastic that was faced approximately 0.125 inch (3.2 mm) deep into the specimen, polished, and chemically etched with a solution of 97 percent $H_2O$, 2 percent $HNO_3$, and 1 percent HF, by volume. A few specimens were face mounted to study the extent of surface cracking. Crack penetration into the specimens was measured by using a microscope with a micrometer eyepiece.

## EFFECT OF RESIDUAL STRESS ON SALT-STRESS-CORROSION CRACKING

### Continuous Exposure

Results for reverse-bend tests run on bare specimens are listed in table I(a) and are shown in figures 5 and 6. These tests are designated as control tests and indicate no stress-corrosion cracking for continuous exposure times up to 700 hours at 550° F (561° K). There does appear to be a slight aging effect for the cold-worked duplex-annealed titanium as evidenced by the 10-percent increase in maximum load and 10-percent decrease in deflection at maximum load with exposure time.

Test results for the salt-coated specimens are listed in table I(b) and are shown in figure 5. Figure 5(a) shows typical load-deflection curves for various exposure times. The change in bending deflection at maximum load is a more sensitive indicator of corrosion cracking than the change in maximum load. This sensitivity can readily be seen in figure 5(a). The increasing severity of salt-stress-corrosion cracking with exposure time is shown in figure 5(b) as a reduction in the relative deflection at maximum load. Relative deflection is defined as the ratio of the deflection at maximum load for exposed specimens to the deflection at maximum load for unexposed specimens. A curve has been drawn through the lower limit of the test data. It appears that corrosion cracking becomes detrimental in less than 100 hours for the salt-coated residually stressed specimens of duplex-annealed titanium. The percent reduction in deflection for the residually stressed specimens is comparable with the percent loss in shortening for the load-induced tensile stressed specimens of mill-annealed Ti-8Al-1Mo-1V with a salt coating. (See ref. 1.)

Corresponding results for tests of residually stressed specimens that had been salt dipped are listed in table I(c) and are shown in figure 6. Comparison of load-deflection curves and the reduction in deflection at maximum load for salt-dipped (fig. 6) and salt-coated (fig. 5) specimens shows that the effects of salt-stress corrosion from the salt dip were more severe than the effects from the salt coating for comparable exposure times. The onset of corrosion cracking appears to occur in less than 20 hours at 550° F (561° K) for salt-dipped residually stressed specimens.

## Cyclic Exposure

On the assumption that some minimum time at temperature is needed to start the cracking, thermal cycling might possibly alleviate or completely remove the corrosion cracking since there appears to be a threshold time of nearly 20 hours continuous exposure before the effects of cracking show up. The results of cyclic exposure to 550° F (561° K) for salt-dipped residually stressed specimens are given in table II and are shown in figure 7. Cycle times of 2, 4, 6, 8, and 16 hours at temperature were investigated.

Definite evidence of the detrimental effects of corrosion cracking is shown in figure 7 for all cycle times. However, there appears to be less effect, as measured by the relative deflection at failure, for the shorter cycle times of 2 and 4 hours than for continuous exposure after any specified accumulated exposure time. For the longer cycle times of 6, 8, and 16 hours, the test results generally fall within the limits of scatter for continuous exposure.

## Metallurgical Examination

Photomicrographs of typical cracks resulting from salt-stress corrosion are reproduced as figures 8 and 9. Figure 8 shows the crack penetration into the tensile region of a residually stressed specimen after 96 hours of exposure. All the cracks occur on the inside of the bend radius. The lack of continuity of crack length is shown in figure 9, which is a photomicrograph of another specimen showing a section cut parallel to a plane tangent to the curved surface. Both figures indicate the intergranular nature of the crack penetration.

Measurements were made of the depth of crack penetration for each crack in a number of specimens after various exposure times and the results are plotted in figure 10. The width of the band at any given time shows that considerable scatter exists, possibly owing to differences in crack propagation rate and in crack nucleation time as a result of specimen surface variations. For example, in figure 8 at least eight cracks, varying in depth by a factor of at least three, are visible. A curve has been faired through the upper limits of crack penetration in figure 10, and from this curve the rate of crack growth as a function of exposure time has been calculated. Rate of crack growth is plotted in figure 11, which shows that the maximum rate of growth occurs when the crack is initiated. That the rate of growth diminishes rapidly with exposure time might be expected for at least two reasons. First, as the crack penetrates deeper, the tip of the crack becomes further removed from the dry salt layer on the surface. Second, as the crack penetrates deeper, it enters progressively lower tensile stress regions in the fabricated bend region.

# METHODS FOR ALLEVIATING RESIDUAL STRESS EFFECTS

In view of the severity of salt-stress-corrosion cracking on fabricated bend regions with only a single dip in salt water, several approaches to alleviate this cracking have been examined in a preliminary manner. These various approaches are discussed in the following paragraphs and the results are given in table III and figure 12.

## Stress Relief by Annealing

Because of the necessity for both salt and stress at elevated temperature to produce corrosion cracking, any process which will reduce or eliminate the stress should alleviate the cracking. Stress relief by annealing is generally considered to be a process which reduces fabrication stresses. Accordingly, one group of 10 fabricated specimens were stress relieved in vacuum at $1200^{\circ}$ F ($922^{\circ}$ K) for 1 hour as suggested in reference 5. After subsequent exposure to $550^{\circ}$ F ($561^{\circ}$ K) with a salt dip, these specimens were more severely cracked than comparable specimens without the stress relief. As this result was contrary to expectation, the titanium material producer was contacted for specific stress-relief data for duplex-annealed Ti-8Al-1Mo-1V. The producer's recommended treatment consisted of 1/4-hour exposure at $1450^{\circ}$ F ($1061^{\circ}$ K) in air followed by air cooling, descaling, and pickling.

Fabricated specimens were stress relieved in two separate batches to check reproducibility in accordance with the producer's recommendations except that the exposure was carried out in argon rather than air. The light oxide that formed during air cooling was removed by pickling. Three specimens were next oxidized for 24 hours at $500^{\circ}$ F ($533^{\circ}$ K). After these thermal treatments, specimens were salt dipped and exposed. As shown in figure 12, the stress relief did not alleviate the effects of salt-stress-corrosion cracking. No differences could be observed between the two batches or between "pickled and salted" and "pickled, oxidized, and salted" specimens. (See table III(a).)

As a part of a continuing investigation, three additional stress-relief runs have been made with a modified residually stressed specimen. These runs were made in air: one at $1450^{\circ}$ F ($1061^{\circ}$ K) for 1/4 hour, one at $1450^{\circ}$ F ($1061^{\circ}$ K) for 1/2 hour, and one at $1650^{\circ}$ F ($1172^{\circ}$ K) for 1/4 hour. None of these produced any alleviation of the effects of salt-stress-corrosion cracking; it appears that the stress is not being relieved sufficiently by the present processes. Longer times and higher temperatures may be necessary.

## Vibratory Finish

In order to speed up fabrication by eliminating hand deburring, one group of specimens were given a vibratory treatment to remove shearing burrs from the blanks prior to brake forming. This treatment consisted of immersion in a box filled with aluminum oxide triangles (1/4 inch by 5/8 inch (6.4 mm by 15.9 mm)), grinding compound, and water. The box was vibrated for 6 hours at a frequency of about 30 cycles per second (30 Hz), which was sufficient to impart a rolling motion to the entire mass. Burrs were removed, all edges were slightly rounded, and the flat surfaces appeared to be lightly roughened in the process; however, a surface roughness test showed no greater roughness than that of the "as rolled" sheet. Figure 12 indicates that this vibratory treatment prior to forming had no beneficial effects on salt-stress-corrosion cracking. Apparently any compression prestress imparted to the specimen surface was completely overcome by the subsequent brake forming.

Because the vibratory treatment has had quite a marked effect on improving the resistance to salt-stress-corrosion cracking for other types of specimens, an investigation is in progress with residually stressed specimens given the vibratory treatment after brake forming. Preliminary results indicate partial effectiveness; however, additional work is needed.

### Shot Peening

Two groups of specimens were given a shot peening treatment after brake forming to impart a compressive residual stress to all surfaces. Glass particles $\left(SiO_2\right)$ of a coarse size (250 to 500 microns (250 to 500 μm) in diameter) and of a fine size (44 to 74 microns (44 to 74 μm) in diameter) were used as shot to minimize the possibility of a surface contamination.

The shot peening appears to be partially effective in reducing the magnitude of the salt-stress-corrosion cracking (see fig. 12); however, it also reduces the amount of reverse bending deflection for the specimens prior to exposure with a salt dip. Further work with this type of alleviation appears to be desirable.

### Nickel Plating

One group of fabricated specimens were electroplated with a nickel coating 0.0003 to 0.0005 inch (8 to 13 μm) thick. These were then salt dipped and exposed for various times. The nickel plating appears to be effective in preventing salt-stress-corrosion cracking for significant times. (See fig. 12 and table III(e).) Further work with nickel plating appears warranted.

## CONCLUSIONS

The following conclusions are drawn from the experimental investigation of salt-stress-corrosion cracking of residually stressed specimens of duplex-annealed Ti-8Al-1Mo-1V sheet exposed to $550^\circ$ F ($561^\circ$ K):

1. Residual stresses can cause corrosion cracking as severe as the cracking caused by load-induced tensile stresses.

2. A single dip in a 3.4-percent solution of NaCl in water produces more detrimental corrosion than a heavy salt crust.

3. Crack penetration begins at a high rate in less than 20 hours exposure for salt-dipped specimens, but the rate decreases rapidly with increasing exposure time.

4. Thermal cycling with 2- and 4-hour cycles reduces the severity of corrosion cracking from that experienced with continuous exposure, but does not eliminate the cracking.

5. Stress relief by annealing to the extent studied was not effective in reducing the corrosion effects.

6. Surface treatment by vibratory process, shot peening, and nickel plating appear promising for inhibiting salt-stress-corrosion cracking.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 23, 1964.

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TABLE I.- RESULTS FOR REVERSE-BEND TESTS OF RESIDUALLY STRESSED SPECIMENS OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V SHEET AFTER CONTINUOUS EXPOSURE TO 550° F (561° K)

| Specimen | Exposure time, hr | Maximum load | | Deflection at maximum load | | |
|---|---|---|---|---|---|---|
| | | lb | kN | in. | mm | Percent[1] |
| (a) Control tests, no salt coating | | | | | | |
| 1 | 0 | 310 | 1.38 | 0.264 | 6.7 | 120 |
| 2 | 0 | 303 | 1.35 | .219 | 5.6 | 100 |
| 3 | 0 | 308 | 1.37 | .211 | 5.4 | 96 |
| 4 | 22 | 313 | 1.39 | .215 | 5.5 | 98 |
| 5 | 48 | 320 | 1.42 | .207 | 5.3 | 94 |
| 6 | 196 | 306 | 1.36 | .206 | 5.2 | 94 |
| 7 | 263 | 310 | 1.38 | .230 | 5.8 | 105 |
| 8 | 360 | 318 | 1.41 | .194 | 4.9 | 88 |
| 9 | 484 | 319 | 1.42 | .195 | 5.0 | 89 |
| 10 | 677 | 338 | 1.50 | .193 | 4.9 | 88 |
| 11 | 716 | 310 | 1.38 | .200 | 5.1 | 91 |
| (b) Salt-coated specimens | | | | | | |
| 12 | 97 | 298 | 1.33 | 0.177 | 4.5 | 80 |
| 13 | 168 | 284 | 1.26 | .155 | 3.9 | 70 |
| 14 | 196 | 275 | 1.22 | .139 | 3.5 | 63 |
| 15 | 263 | 275 | 1.22 | .120 | 3.0 | 55 |
| 16 | 360 | 296 | 1.32 | .130 | 3.3 | 59 |
| 17 | 488 | 277 | 1.23 | .111 | 2.8 | 50 |
| 18 | 488 | 266 | 1.18 | .070 | 1.8 | 32 |
| 19 | 677 | 249 | 1.11 | .092 | 2.3 | 42 |
| 20 | 716 | 276 | 1.23 | .127 | 3.2 | 58 |
| 21 | 984 | 245 | 1.09 | .069 | 1.8 | 31 |
| 22 | 984 | 273 | 1.21 | .100 | 2.5 | 45 |
| 23 | 1200 | 264 | 1.17 | .086 | 2.2 | 39 |
| 24 | 1440 | 217 | .97 | .062 | 1.6 | 28 |
| 25 | 1440 | 251 | 1.12 | .086 | 2.2 | 39 |
| 26 | 1800 | 248 | 1.10 | .070 | 1.8 | 32 |
| 27 | 1800 | 203 | .90 | .050 | 1.3 | 23 |

[1]Percentage based on a deflection of 0.22 in. (5.59 mm), which was taken as a weighted average deflection of 100 percent for control tests with no salt and no exposure.

TABLE I.- RESULTS FOR REVERSE-BEND TESTS OF RESIDUALLY STRESSED SPECIMENS OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V SHEET AFTER CONTINUOUS EXPOSURE TO 550° F (561° K) - Concluded

| Specimen | Exposure time, hr | Maximum load | | Deflection at maximum load | | |
|---|---|---|---|---|---|---|
| | | lb | kN | in. | mm | Percent[1] |
| (c) Salt-dipped specimens | | | | | | |
| 28 | 22 | 312 | 1.39 | 0.190 | 4.8 | 86 |
| 29 | 22 | 297 | 1.32 | .187 | 4.8 | 85 |
| 30 | 22 | 300 | 1.33 | .198 | 5.0 | 90 |
| 31 | 48 | 284 | 1.26 | .126 | 3.2 | 57 |
| 32 | 48 | 307 | 1.37 | .166 | 4.2 | 76 |
| 33 | 48 | 286 | 1.27 | .142 | 3.6 | 64 |
| 34 | 48 | 292 | 1.30 | .144 | 3.7 | 65 |
| 35 | 72 | 251 | 1.12 | .116 | 2.9 | 53 |
| 36 | 72 | 287 | 1.28 | .159 | 4.0 | 72 |
| 37 | 72 | 281 | 1.25 | .155 | 3.9 | 70 |
| 38 | 96 | 256 | 1.14 | .105 | 2.7 | 48 |
| 39 | 96 | 234 | 1.04 | .072 | 1.8 | 33 |
| 40 | 97 | 262 | 1.17 | .098 | 2.5 | 45 |
| 41 | 97 | 273 | 1.21 | .102 | 2.6 | 46 |
| 42 | 97 | 263 | 1.17 | .116 | 2.9 | 53 |
| 43 | 97 | 248 | 1.10 | .088 | 2.2 | 40 |
| 44 | 97 | 281 | 1.25 | .144 | 3.7 | 65 |
| 45 | 121 | 285 | 1.27 | .128 | 3.3 | 58 |
| 46 | 121 | 256 | 1.14 | .093 | 2.4 | 42 |
| 47 | 139 | 269 | 1.20 | .099 | 2.5 | 45 |
| 48 | 139 | 280 | 1.25 | .111 | 2.8 | 50 |
| 49 | 188 | 258 | 1.15 | .111 | 2.8 | 50 |
| 50 | 360 | 263 | 1.17 | .122 | 3.1 | 55 |
| 51 | 408 | 238 | 1.06 | .069 | 1.8 | 31 |
| 52 | 408 | 246 | 1.09 | .084 | 2.1 | 38 |
| 53 | 408 | 242 | 1.08 | .071 | 1.8 | 32 |
| 54 | 507 | 214 | .95 | .054 | 1.4 | 25 |
| 55 | 507 | 235 | 1.05 | .058 | 1.5 | 26 |
| 56 | 507 | 223 | .99 | .073 | 1.9 | 33 |
| 57 | 699 | 210 | .93 | .058 | 1.5 | 26 |

[1]Percentage based on a deflection of 0.22 in. (5.59 mm), which was taken as a weighted average deflection of 100 percent for control tests with no salt and no exposure.

TABLE II.- RESULTS FOR REVERSE-BEND TESTS OF SALT-DIPPED RESIDUALLY STRESSED SPECIMENS OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V SHEET AFTER CYCLIC EXPOSURE TO 550° F (561° K)

| Specimen | Cycle time at temperature, hr | Accumulated time, hr | Maximum load | | Deflection at maximum load | | |
|---|---|---|---|---|---|---|---|
| | | | lb | kN | in. | mm | Percent[1] |
| 58 | 16 | 48 | 289 | 1.29 | 0.123 | 3.1 | 56 |
| 59 | | 48 | 303 | 1.35 | .140 | 3.6 | 64 |
| 60 | | 48 | 292 | 1.30 | .110 | 2.8 | 50 |
| 61 | | 96 | 309 | 1.37 | .148 | 3.8 | 67 |
| 62 | | 96 | 304 | 1.35 | .127 | 3.2 | 58 |
| 63 | | 96 | 288 | 1.28 | .118 | 3.0 | 54 |
| 64 | 8 | 48 | 320 | 1.42 | .162 | 4.1 | 74 |
| 65 | | 48 | 298 | 1.33 | .165 | 4.2 | 75 |
| 66 | | 48 | 333 | 1.48 | .149 | 3.8 | 68 |
| 67 | | 96 | 293 | 1.30 | .121 | 3.1 | 55 |
| 68 | | 96 | 319 | 1.42 | .115 | 2.9 | 52 |
| 69 | | 96 | 282 | 1.25 | .113 | 2.9 | 51 |
| 70 | 6 | 90 | 312 | 1.39 | .171 | 4.3 | 78 |
| 71 | | 90 | 327 | 1.45 | .158 | 4.0 | 72 |
| 72 | | 90 | 300 | 1.33 | .136 | 3.5 | 62 |
| 73 | | 330 | 305 | 1.36 | .107 | 2.7 | 49 |
| 74 | | 330 | 312 | 1.39 | .117 | 3.0 | 53 |
| 75 | | 330 | 308 | 1.37 | .101 | 2.6 | 46 |
| 76 | 4 | 104 | 351 | 1.56 | .193 | 4.9 | 88 |
| 77 | | 104 | 315 | 1.40 | .185 | 4.7 | 84 |
| 78 | | 104 | 327 | 1.45 | .195 | 5.0 | 89 |
| 79 | | 300 | 310 | 1.38 | .133 | 3.4 | 60 |
| 80 | | 300 | 313 | 1.39 | .132 | 3.4 | 60 |
| 81 | | 300 | 283 | 1.26 | .104 | 2.6 | 47 |
| 82 | | 500 | 337 | 1.50 | .128 | 3.3 | 58 |
| 83 | | 500 | 314 | 1.40 | .147 | 3.7 | 67 |
| 84 | | 500 | 349 | 1.55 | .172 | 4.4 | 78 |
| 85 | 2 | 96 | 330 | 1.47 | .185 | 4.7 | 84 |
| 86 | | 96 | 343 | 1.53 | .183 | 4.6 | 83 |
| 87 | | 96 | 316 | 1.41 | .188 | 4.8 | 86 |
| 88 | | 312 | 339 | 1.51 | .172 | 4.4 | 78 |
| 89 | | 312 | 357 | 1.59 | .136 | 3.5 | 62 |
| 90 | | 312 | 328 | 1.46 | .166 | 4.2 | 75 |
| 91 | | 530 | 334 | 1.49 | .179 | 4.6 | 81 |
| 92 | | 530 | 326 | 1.45 | .171 | 4.3 | 78 |
| 93 | | 530 | 360 | 1.60 | .184 | 4.7 | 84 |

[1]Percentage based on a deflection of 0.22 in. (5.59 mm), which was taken as a weighted average deflection of 100 percent for control tests with no salt and no exposure.

TABLE III.- RESULTS FOR REVERSE-BEND TESTS OF SPECIMENS WHICH HAVE RECEIVED VARIOUS TREATMENTS TO ALLEVIATE SALT-STRESS CORROSION

[Specimens treated, salt dipped, then exposed at 550° F (561° K)]

| Specimen | Exposure time, hr | Maximum load | | Deflection at maximum load | | |
|---|---|---|---|---|---|---|
| | | lb | kN | in. | mm | Percent[1] |
| (a) Stress relieved by annealing 1/4 hour at 1450° F (1061° K) in argon; air cooled, pickled in 15% $HNO_3$ + 2% HF + 83% $H_2O$ | | | | | | |
| Batch 1 | | | | | | |
| 94 | 0 | 320 | 1.42 | 0.237 | 6.0 | 108 |
| 95 | 0 | 326 | 1.45 | .235 | 6.0 | 107 |
| 96 | 118 | 250 | 1.11 | .078 | 2.0 | 35 |
| 97 | 118 | 250 | 1.11 | .073 | 1.9 | 33 |
| 98 | 118 | 240 | 1.07 | .068 | 1.7 | 31 |
| 99 | 365 | 236 | 1.05 | .062 | 1.6 | 28 |
| 100 | 365 | 268 | 1.19 | .071 | 1.8 | 32 |
| 101 | 365 | 253 | 1.13 | .074 | 1.9 | 34 |
| 102 | 365 | 222 | .99 | .062 | 1.6 | 28 |
| 103 | 365 | 225 | 1.00 | .059 | 1.5 | 27 |
| Batch 2 | | | | | | |
| 104 | [2]0 | 303 | 1.35 | 0.223 | 5.7 | 101 |
| 105 | [2]100 | 239 | 1.06 | .081 | 2.1 | 37 |
| 106 | [2]100 | 237 | 1.05 | .073 | 1.9 | 33 |
| 107 | 100 | 237 | 1.05 | .080 | 2.0 | 36 |
| 108 | 100 | 240 | 1.07 | .075 | 1.9 | 34 |
| (b) Vibratory finish prior to forming | | | | | | |
| 109 | 0 | 298 | 1.33 | 0.268 | 6.8 | 122 |
| 110 | 0 | 280 | 1.25 | .240 | 6.1 | 109 |
| 111 | 0 | 276 | 1.23 | .230 | 5.8 | 105 |
| 112 | 0 | 275 | 1.22 | .253 | 6.4 | 115 |
| 113 | 100 | 226 | 1.01 | .122 | 3.1 | 55 |
| 114 | 100 | 222 | .99 | .104 | 2.6 | 47 |
| 115 | 100 | 208 | .93 | .092 | 2.3 | 42 |
| 116 | 100 | 212 | .94 | .098 | 2.5 | 45 |
| 117 | 200 | 237 | 1.05 | .130 | 3.3 | 59 |
| 118 | 200 | 229 | 1.02 | .124 | 3.1 | 56 |
| 119 | 200 | 220 | .98 | .100 | 2.5 | 45 |
| 120 | 200 | 235 | 1.05 | .133 | 3.4 | 60 |

[1]Percentage based on a deflection of 0.22 in. (5.59 mm), which was taken as a weighted average deflection of 100 percent for control tests with no salt and no exposure.

[2]Specimens 104 to 106 were oxidized in air 24 hours at 500° F (533° K) prior to salt dipping and exposure.

TABLE III.- RESULTS FOR REVERSE-BEND TESTS OF SPECIMENS WHICH HAVE RECEIVED VARIOUS TREATMENTS TO ALLEVIATE SALT-STRESS CORROSION - Concluded

[Specimens treated, salt dipped, then exposed at 550° F (561° K)]

| Specimen | Exposure time, hr | Maximum load | | Deflection at maximum load | | |
|---|---|---|---|---|---|---|
| | | lb | kN | in. | mm | Percent[1] |
| (c) Coarse shot peening after forming | | | | | | |
| 121 | 0 | 273 | 1.21 | 0.158 | 4.0 | 72 |
| 122 | 99 | 269 | 1.20 | .136 | 3.5 | 62 |
| 123 | 268 | 275 | 1.22 | .132 | 3.4 | 60 |
| 124 | 600 | 267 | 1.19 | .108 | 2.7 | 49 |
| (d) Fine shot peening after forming | | | | | | |
| 125 | 0 | 287 | 1.28 | 0.186 | 4.7 | 84 |
| 126 | 99 | 283 | 1.26 | .161 | 4.1 | 73 |
| 127 | 268 | 283 | 1.26 | .158 | 4.0 | 72 |
| 128 | 600 | 277 | 1.23 | .153 | 3.9 | 70 |
| (e) Nickel plated after forming | | | | | | |
| 129 | 0 | 306 | 1.36 | 0.208 | 5.3 | 94 |
| 130 | 0 | 289 | 1.29 | .220 | 5.6 | 100 |
| 131 | 220 | 304 | 1.35 | .191 | 4.9 | 87 |
| 132 | 410 | 268 | 1.19 | .182 | 4.6 | 83 |
| 133 | 508 | 308 | 1.37 | .192 | 4.9 | 87 |
| 134 | 696 | 291 | 1.29 | .137 | 3.5 | 62 |
| 135 | 888 | 289 | 1.29 | .133 | 3.4 | 60 |
| 136 | 1101 | 285 | 1.27 | .186 | 4.7 | 85 |
| 137 | 2544 | 275 | 1.22 | .136 | 3.5 | 62 |

[1]Percentage based on a deflection of 0.22 in. (5.59 mm), which was taken as a weighted average deflection of 100 percent for control tests with no salt and no exposure.

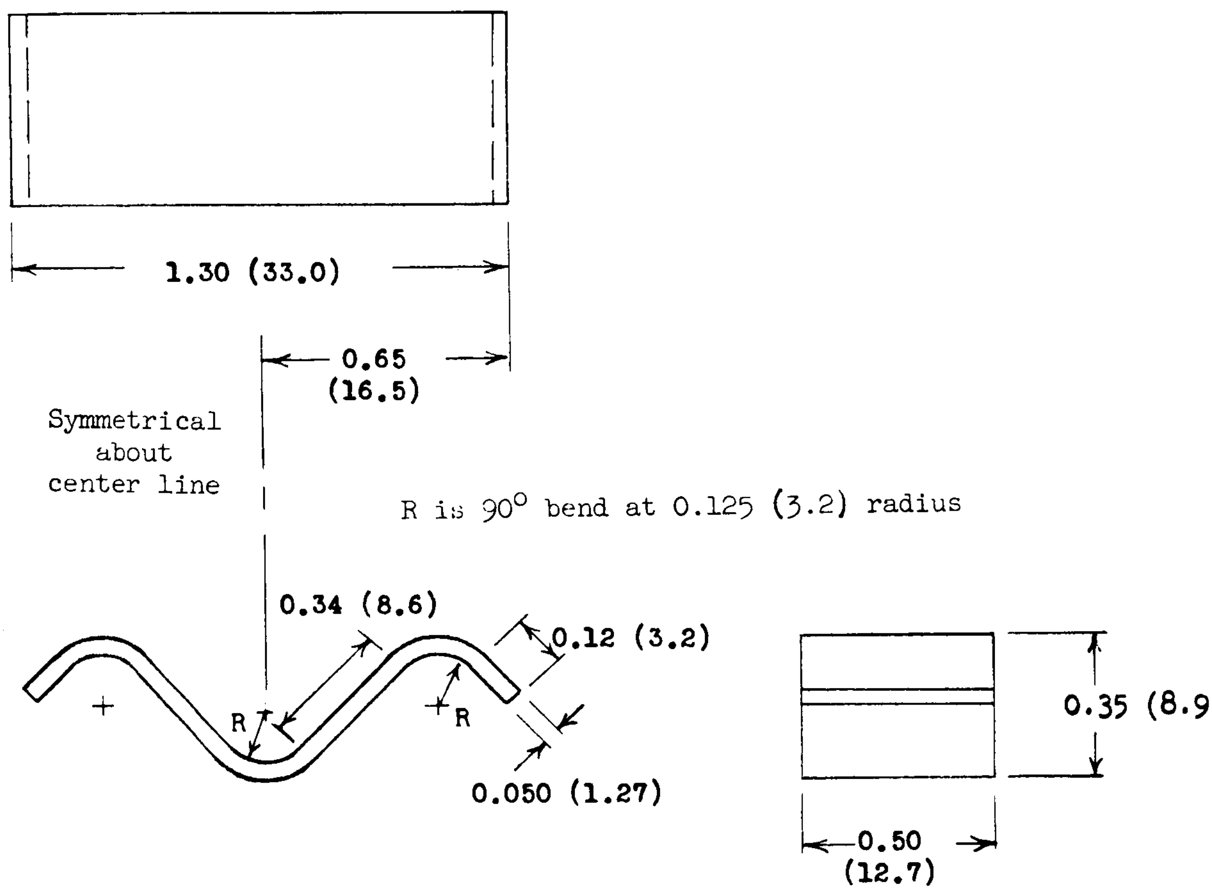



Figure 1.- Residually stressed specimen design. Principal dimensions are in inches; dimensions in parentheses are in millimeters.

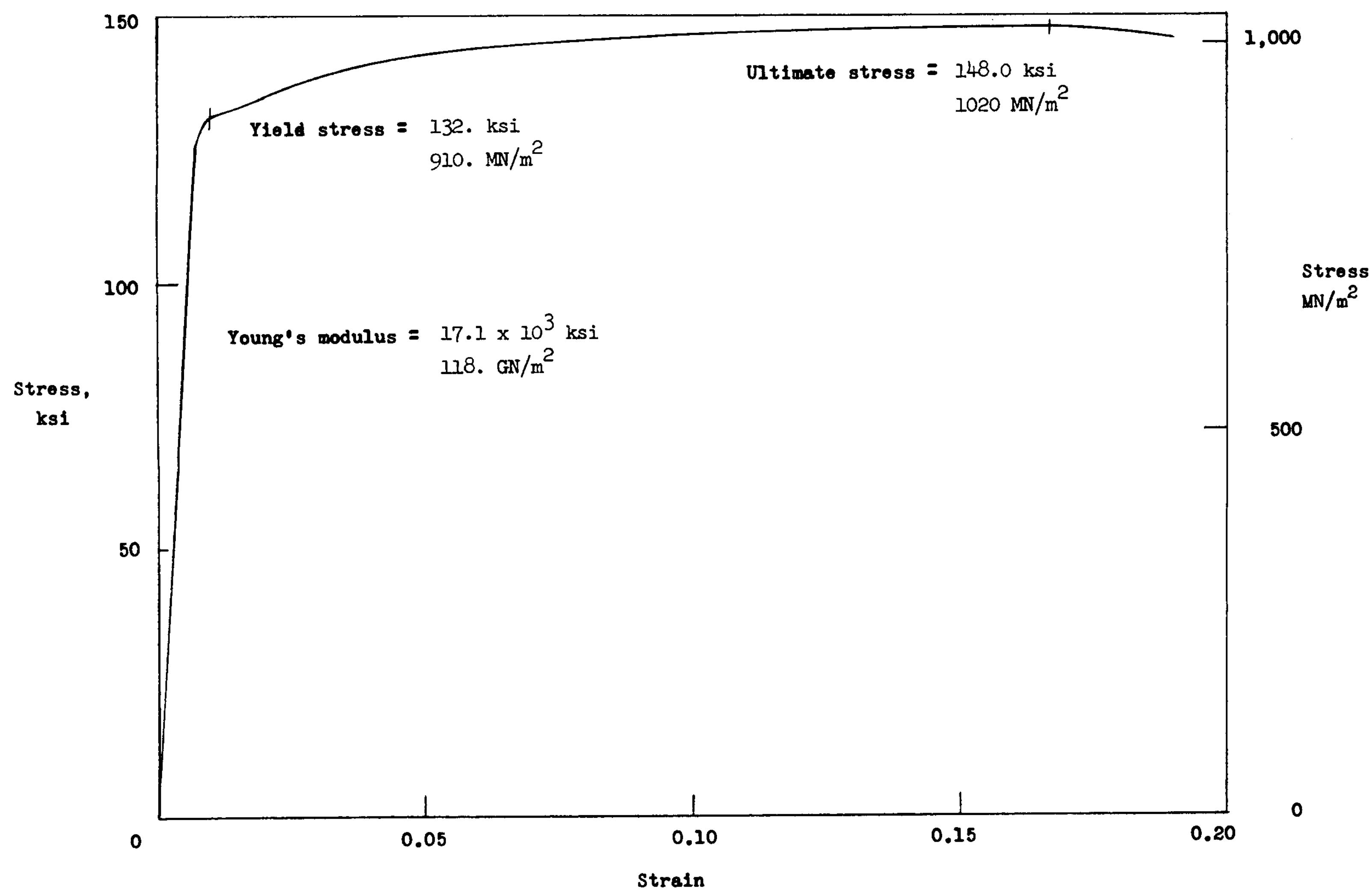
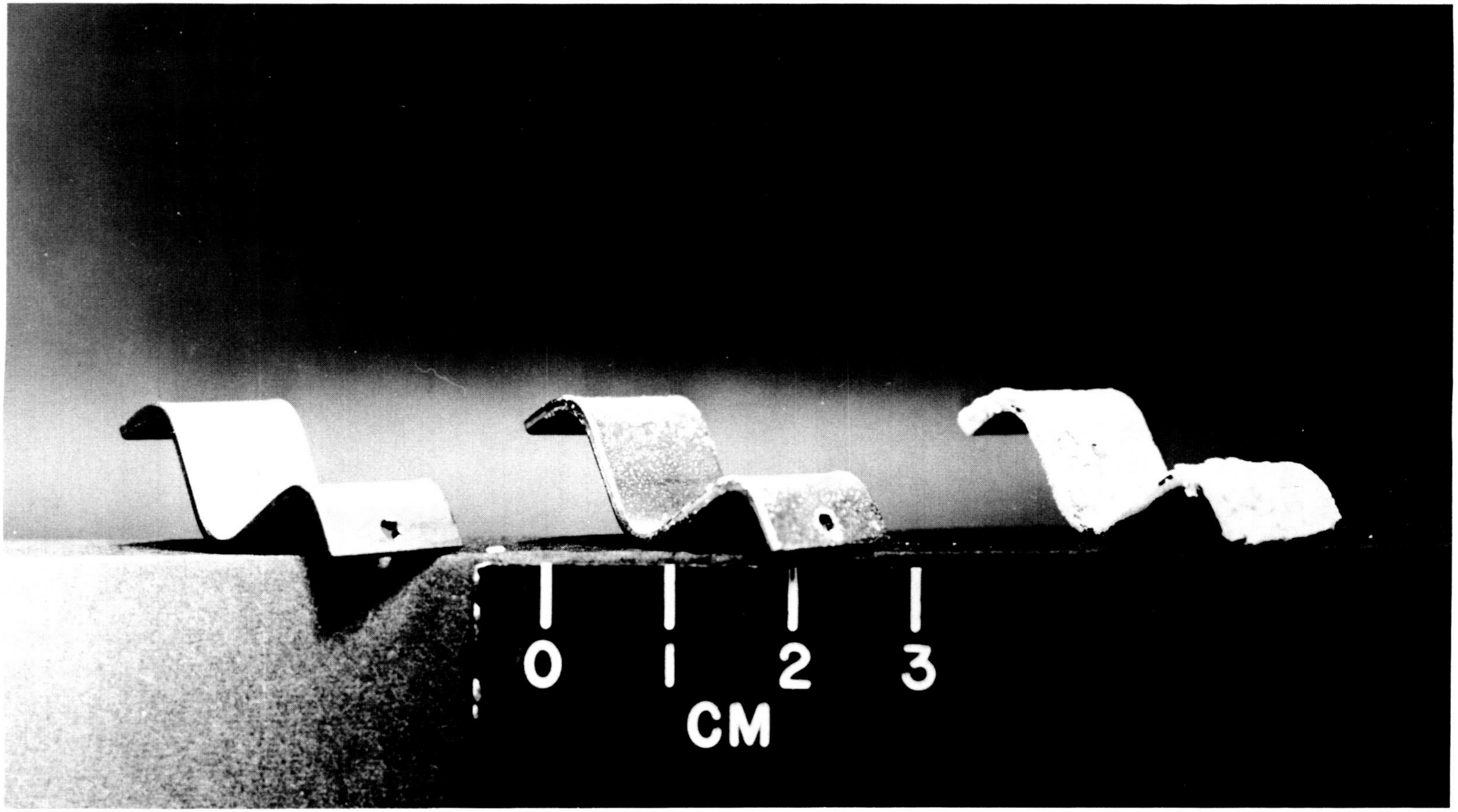
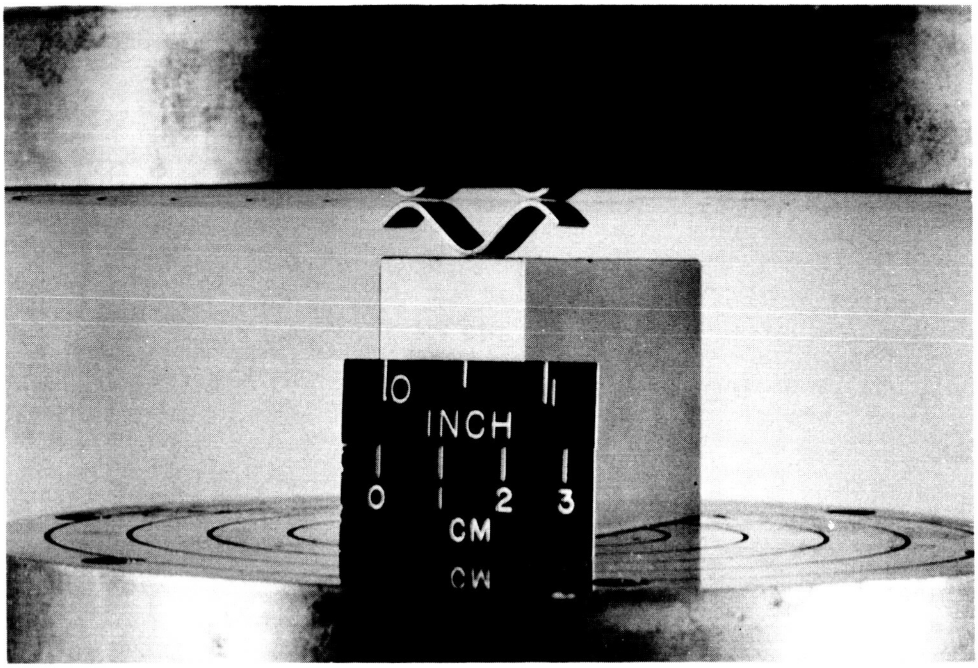



Figure 2.- Tensile stress-strain curve for duplex-annealed Ti-8Al-1Mo-1V sheet.

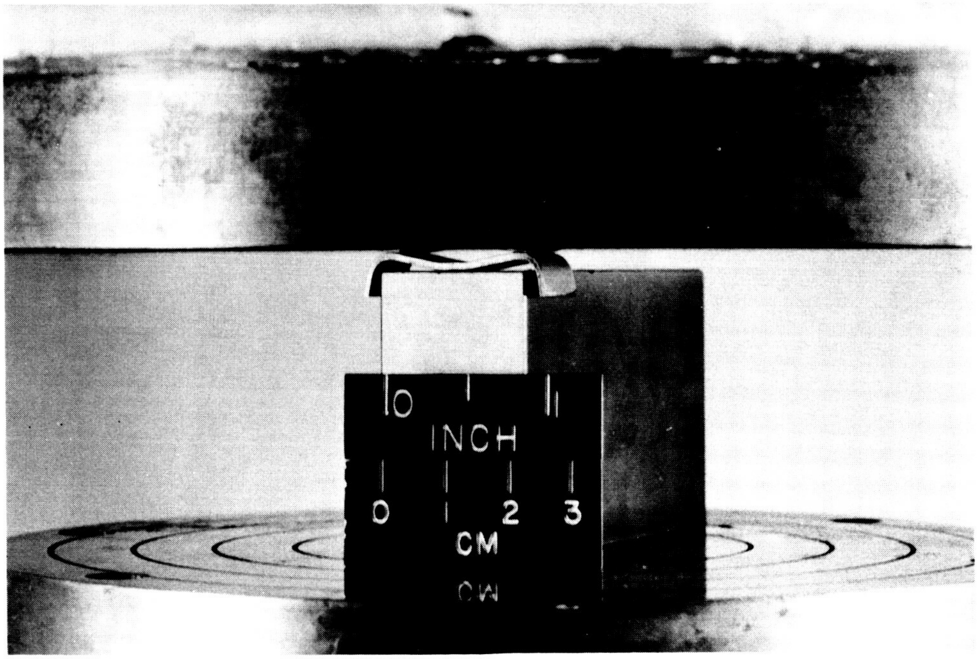



L-64-1993

Figure 3.- Specimens before and after salt application. Bare, salt-dipped, and salt-coated specimens.

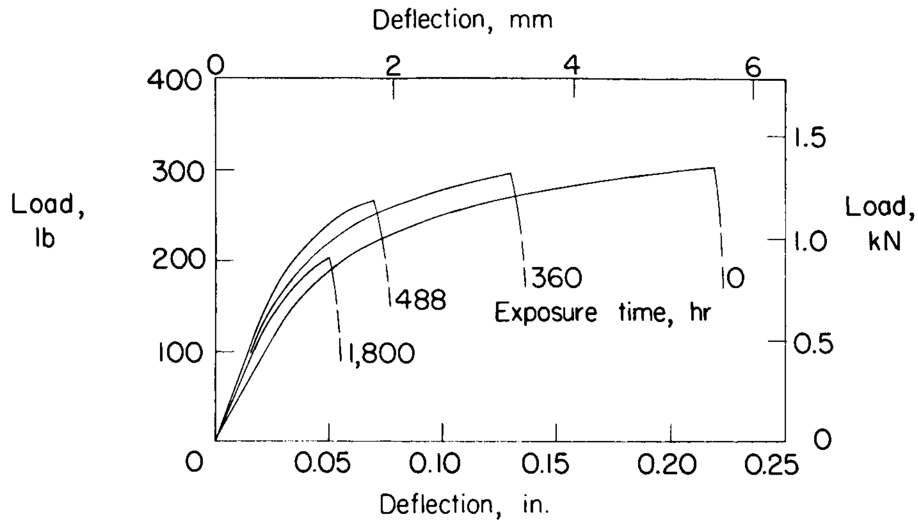



(a) Start of loading. L-64-2017

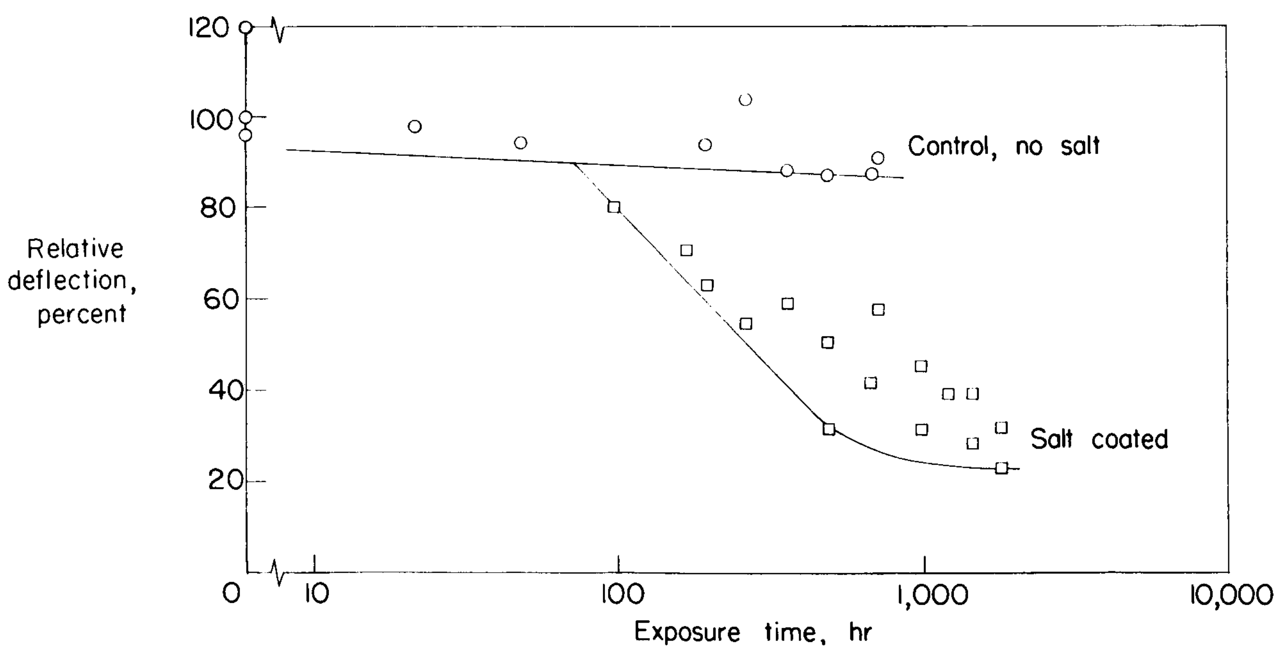



(b) At maximum load for bare specimen. L-64-2018

Figure 4.- Reverse-bend compression test to determine existence of salt-stress-corrosion cracking.

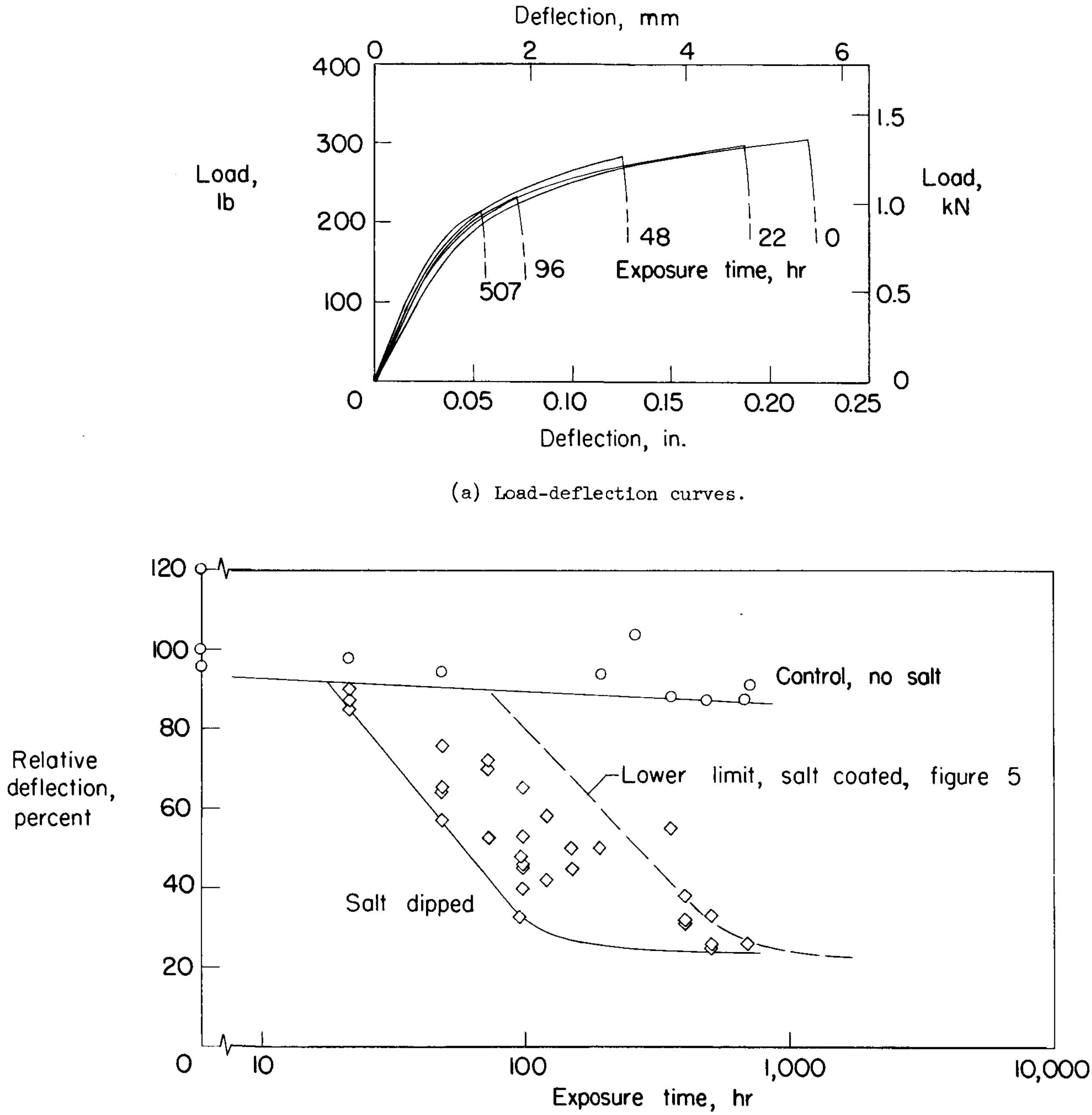



(a) Load-deflection curves.




(b) Reduction in deflection at maximum load.

Figure 5.- Effects of corrosion cracking on load-deflection curves and on relative deflection at failure of residually stressed, salt-coated Ti-8Al-1Mo-1V specimens exposed at 550° F (561° K).




(a) Load-deflection curves.



(b) Reduction in deflection.

Figure 6.- Load-deflection curves and relative deflection at failure of residually stressed, salt-dipped Ti-8Al-1Mo-1V specimens exposed at 550° F (561° K).

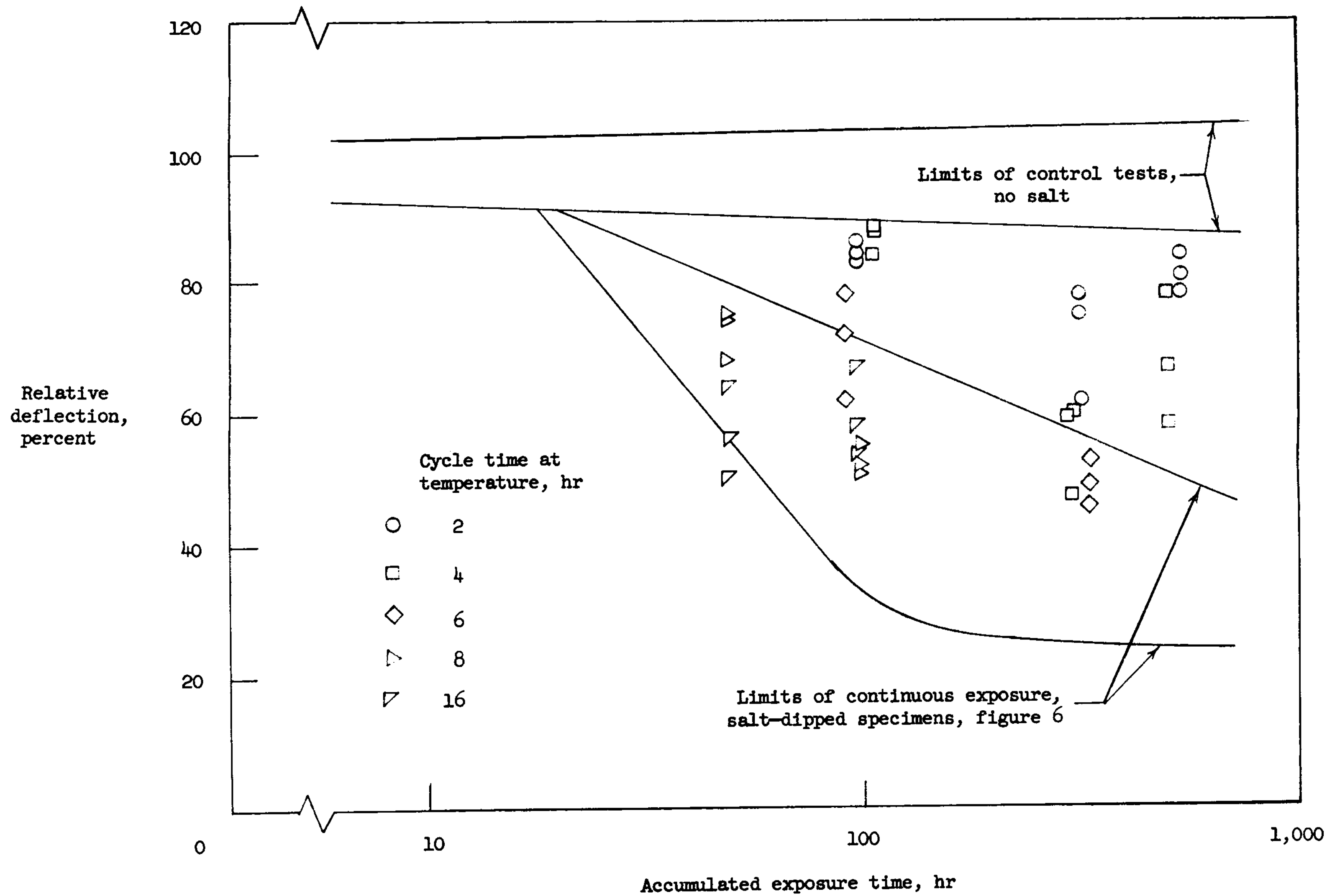
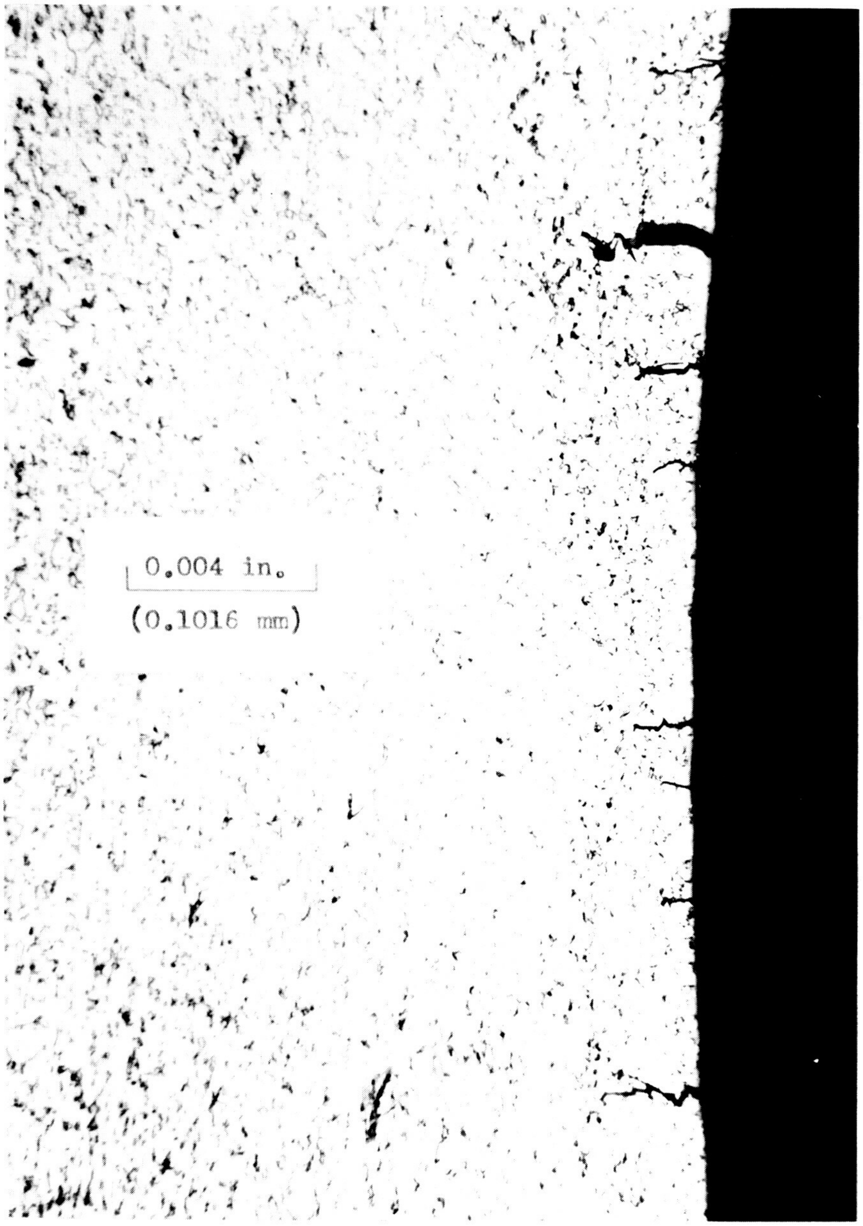
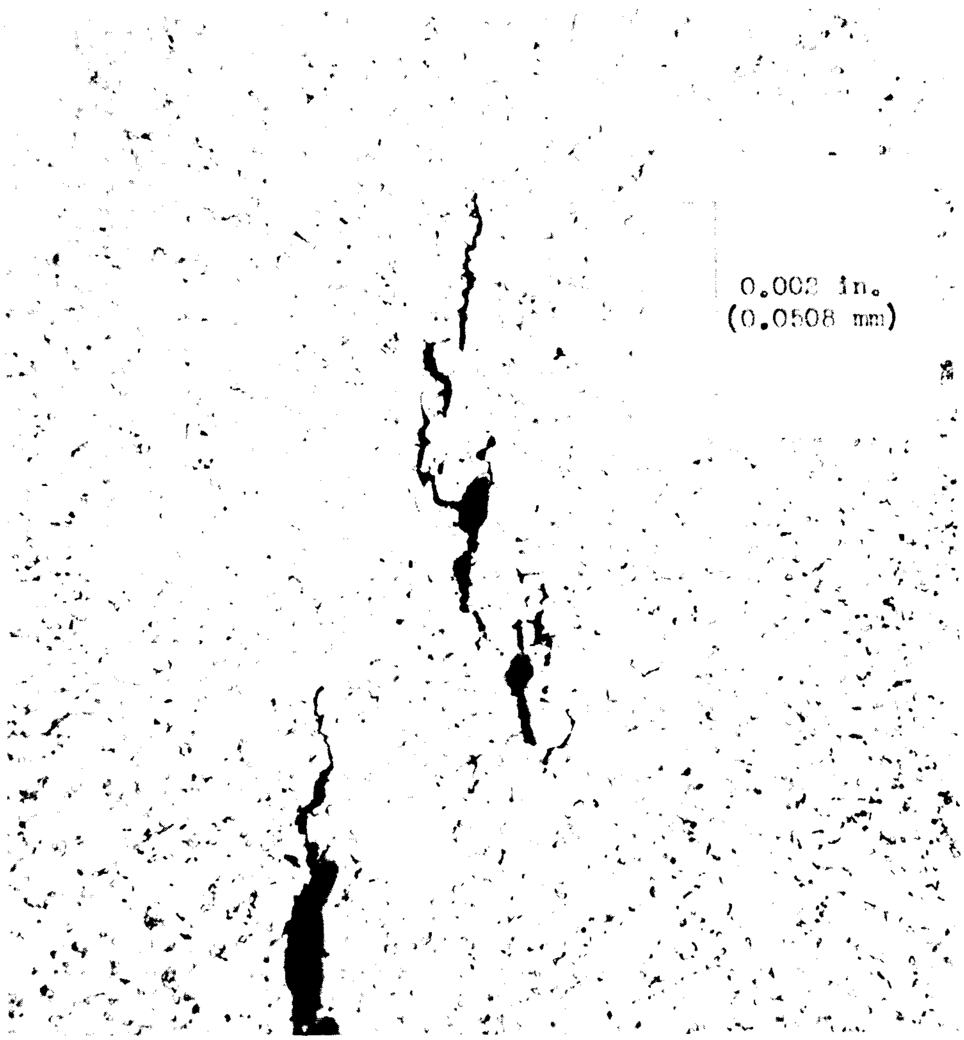



Figure 7.- Cyclic exposure to 550° F (561° K) of residually stressed, salt-dipped Ti-8Al-1Mo-1V specimens.




L-65-6

Figure 8.- Photomicrograph of specimen 39 showing crack formation of residually stressed, salt-dipped Ti-8Al-1Mo-1V exposed at 550° F (561° K) for 96 hours.




L-65-7

Figure 9.- Photomicrograph of specimen 54 showing length and discontinuous nature of cracks in residually stressed, salt-dipped Ti-8Al-1Mo-1V exposed at 550° F (561° K) for 507 hours.

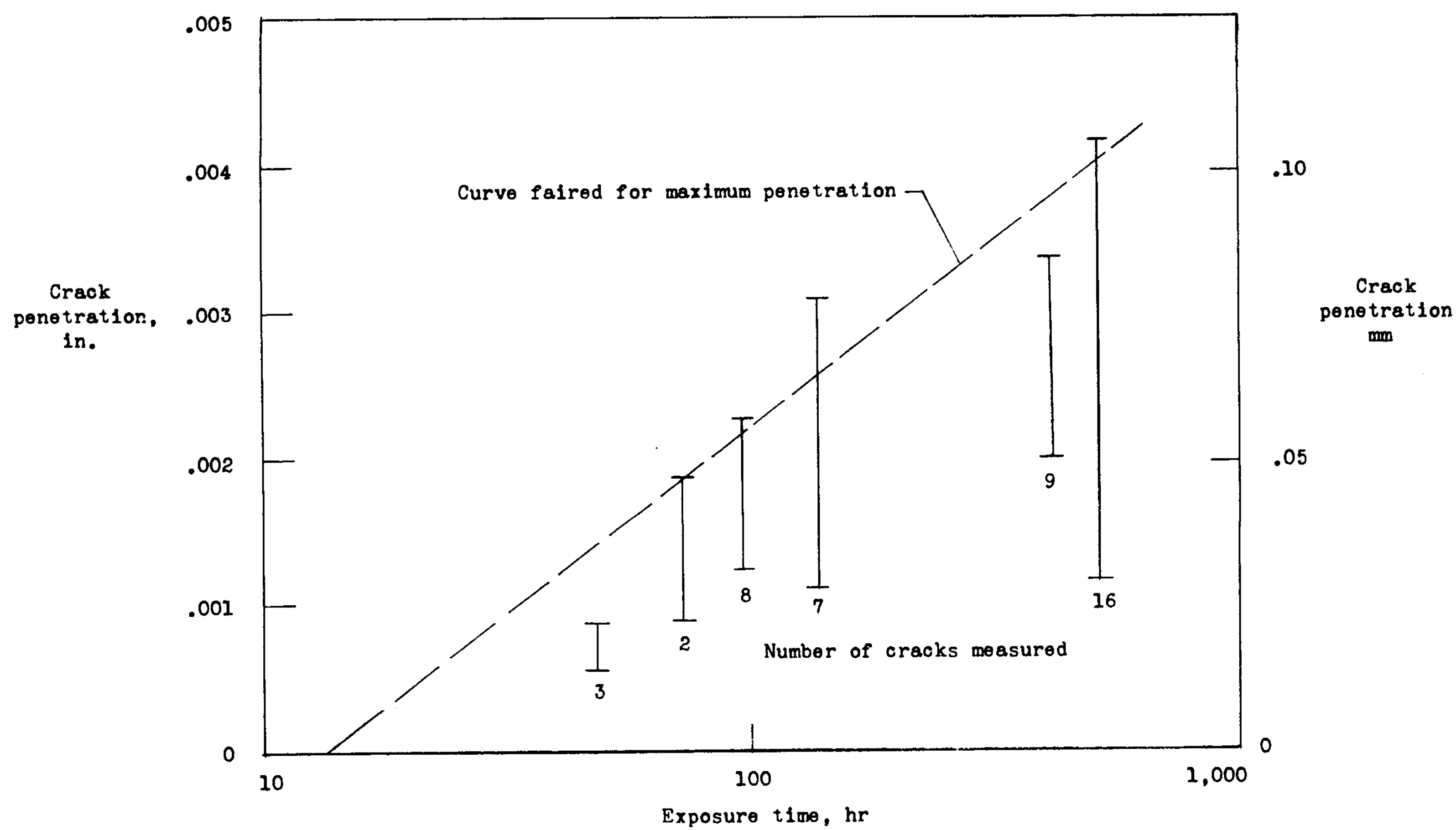



Figure 10.- Depth of crack penetration into residually stressed, salt-dipped Ti-8Al-1Mo-1V specimens after various exposure times at 550° F (561° K).

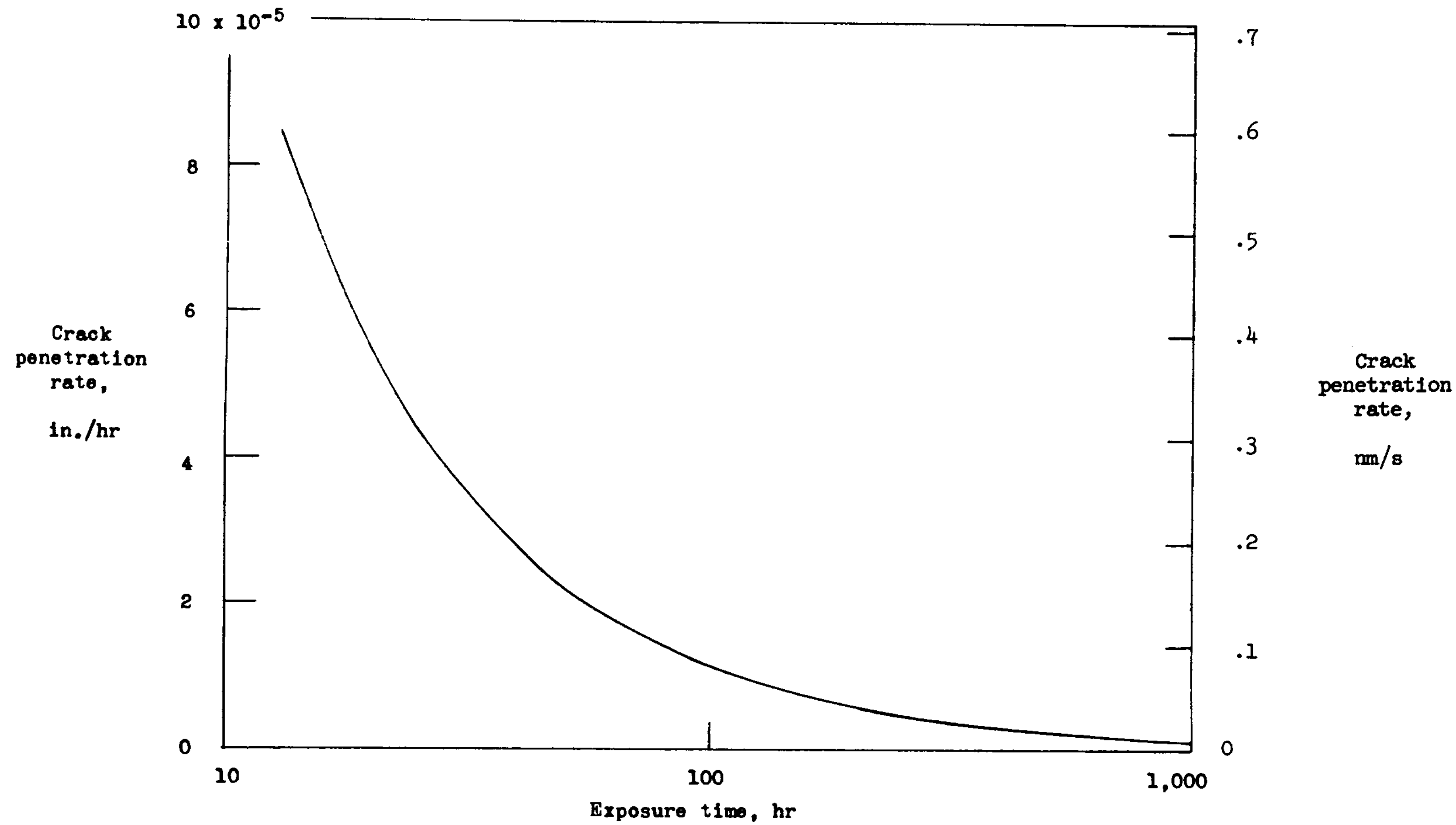



Figure 11.- Rate of crack growth of residually stressed, salt-dipped Ti-8Al-1Mo-1V specimens exposed at 550° F (561° K).

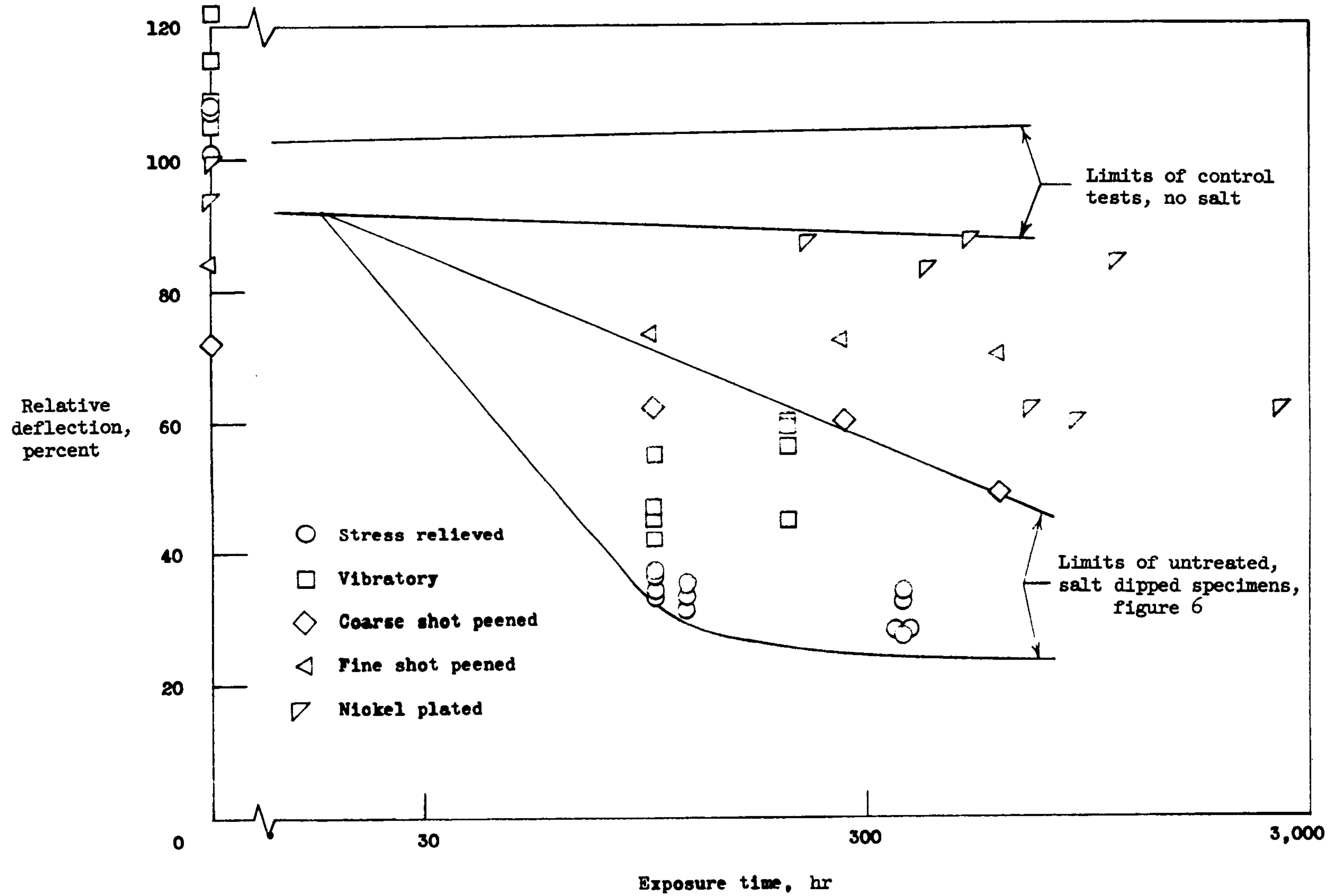



Figure 12.- Various treatments for alleviation of salt-stress-corrosion cracking in residually stressed, salt-dipped Ti-8Al-1Mo-1V specimens exposed at 550° F (561° K).